

Is the Top Quark Really Heavier than the W Boson?

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Scalar induced top decays may drastically suppress $B(t \rightarrow \ell\nu + jet)$ and still hide the top below M_W . The $p\bar{p}$ collider experiments should enlarge the scope and study the $m_t - B(t \rightarrow \ell\nu j)$ plane. Specific model signatures such as $t \rightarrow ch^0 \rightarrow cbb$ (multiple high p_T b -jets) and $t \rightarrow bH^+ \rightarrow bc\bar{s}, b\tau^+\nu$ (with $B(t \rightarrow b\tau\nu) \lesssim 1/3$) should be explored. Without ruling out these possibilities, isolated lepton signals in the future might actually be due to the 4th generation t' or b' quark, while top quark and toponium physics could still turn up at LEP-II.

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When the τ -lepton [1] and the b -quark [2] were discovered in the 1970's, the top quark was thought to be just around the corner, with mass of order 10 – 30 GeV. Shortly after the ARGUS observation of large $B^0-\bar{B}^0$ mixing [3], however, the prejudice started to shift. To date, the top remains elusive. A global fit [4] to LEP and low energy electroweak data suggests a high value of

$$m_t = 150_{-26}^{+23} \pm 16 \text{ GeV}. \quad (1)$$

The published direct search limit by the CDF Collaboration is [5]

$$m_t > 91 \text{ GeV}, \quad (2)$$

based on data collected in the 1989 Tevatron collider run at Fermilab. With an order of magnitude more data from the 1993 collider run, the CDF and D0 collaborations have extended the limit to about 120 GeV [6]. Though not yet conclusive, a handful of events hint at a top mass consistent with the global fit result of eq. (1). Thus, once again we have the expectation that the top is “just around the corner”, and should be discovered in the 1994 Tevatron collider run.

So, the top seems to be very heavy. But what *hard* evidence do we really have? Eq. (1) assumes the 3 generation Standard Model (SM). If the top is in fact relatively light, it actually suggests the existence of *new* weak doublets (or other multiplets) with sizable splittings. Eq. (2) assumes the SM branching ratio

$$B_{s.l.} \equiv B(t \rightarrow \ell^+\nu + X) \simeq \frac{1}{9}. \quad (3)$$

The limit would weaken if $B_{s.l.}$ is far below this value. A weaker limit [7] of $m_t > 55 \text{ GeV}$ is obtained from the measured W width. This limit would soften if the quark mixing element $|V_{tb}| < 1$. The truly model independent limit comes from $Z \rightarrow t\bar{t}$ search [4] at LEP/SLC, $m_t \gtrsim M_Z/2$. Thus, a relatively light top should not be a forgone conclusion.

The mass region that needs special scrutiny is

$$M_Z/2 \lesssim m_t \lesssim M_W + m_b. \quad (4)$$

The reason is as follows. For $m_t > M_W + m_b$, $\Gamma(t \rightarrow bW)$ is rather large, and eq. (3) should hold. However, below the W threshold, $t \rightarrow bW^*$ is suppressed both by phase space (three body) and propagator effects. If new interactions induce *two body* decays, they would be *relatively* enhanced, thereby suppressing $B_{s,l.}$. The new coupling strength should not be much weaker than $SU_L(2)$ gauge coupling, and the modes should be relatively obscure such that they have not yet been studied. *Effectively this can be achieved only by (pseudo)scalar interactions* (including sfermions). Possible scenarios are: $t \rightarrow cb\bar{b}$ where $b\bar{b}$ comes from the decay of a light neutral scalar boson [8,9]; or $t \rightarrow bc\bar{s}$, where $c\bar{s}$ comes from a charged Higgs boson [10]. A third possibility of $t \rightarrow bH^+ \rightarrow b\tau^+\nu$ [11] is unlikely [12] in light of recent limits on $b \rightarrow s\gamma$ from CLEO [13]. The two scenarios lead to $t \rightarrow 3$ jets final state, which is very hard to disentangle in hadronic collisions. We suggest that the newly accumulated data should be used to explore the low m_t possibility of eq. (4), by taking $B_{s,l.}$ as a free parameter. We then comment on means of detecting the specific, new modes, as well as implications of having a light top quark.

The semileptonic decays, except perhaps $t \rightarrow b\tau^+\nu$, are expected to be mediated by the W boson. Eq. (3) assumes $\Gamma^{SM}(t \rightarrow 3 \text{ jets}) \simeq 6 \Gamma(t \rightarrow e^+\nu + \text{jet})$. However, some new interaction could enhance the $t \rightarrow \text{jets}$ mode, that is $\Gamma_{3j} = \Gamma_{3j}^{SM} + \Gamma'_{3j}$, where Γ'_{3j} is the additional 3-jet width. Eq. (3) gets modified by the factor

$$R \equiv B_{s,l.}/B_{s,l.}^{SM} = (1 - B'), \quad (5)$$

where $B' \equiv \Gamma' / (\Gamma_{tot}^{SM} + \Gamma')$ is the new physics branching ratio. It could be other new top decay possibilities, *e.g.* light supersymmetric (SUSY) particles [14].

The search mode branching ratios become

$$\frac{4}{81} (1 - B')^2, \quad \frac{8}{27} (1 - B') \left(1 + \frac{1}{2} B'\right), \quad (6)$$

for $t\bar{t} \rightarrow \ell_1^+ \ell_2^- + \nu\nu + \text{jets}$ and $\ell^\pm + \nu + \text{jets}$, respectively. It is clear that if $B' \sim 1$ (or $B_{s,l.} \rightarrow 0$), the dilepton signature and therefore the limit of eq. (2) would rapidly become ineffective. The weaker limit of $m_t < 77$ GeV [15] (assuming SM) obtained from $\ell^\pm + \nu + \text{jets}$ search, is less sensitive to B' .

To explore the possibility of $B' \sim 1$ ($R \rightarrow 0$), one should keep $B(t \rightarrow \ell^+\nu + X)$ as a free parameter. One has to *purposely* keep the cuts on lepton p_T and missing E_T relatively low, otherwise the signal events might get rejected by stiffer cuts aimed at searching for a heavier top quark. Furthermore, as the expected number of signal events dwindle, a more careful study is needed to suppress background to a level below what has been achieved in the analysis of 1989 data. To the best of our knowledge, this has not yet been done by the experimental collaborations [16].

Let us take theoretical $t\bar{t}$ cross sections and use eq. (6) to scale the m_t limits from 1989 CDF data as function of R . The results are given in Fig. 1, where we have assumed constant efficiencies and acceptance. Clearly, for smaller $B_{s.l.}$, only the experimental groups can give definite curves, but they should in general fall below those shown in Fig. 1. Newer data from 1993 and later runs can be used to extend the excluded domain in the $m_t - B_{s.l.}$ plane. Note that for smaller R , the single lepton signal is more effective. However, *both methods fail in the vicinity of $R \cong 0$* , since the signal would vanish against background.

We turn to specific models that may allow m_t to fall in the range of eq. (4). The first mode is $t \rightarrow ch^0$ followed by $h^0 \rightarrow b\bar{b}$ [8,9], within the context of two Higgs doublet models (2HDM). At first sight this seems absurd, since in standard types of 2HDM, just like in SM, tree level FCNC Higgs couplings are absent by construction [17]. However, this turned out [18] to be an overkill. *Neutral Higgs bosons can have flavor changing neutral couplings (FCNC) λ_{ij} of order $\sqrt{2m_i m_j}/v$, and with normal Higgs boson masses of order the vacuum expectation value v .* The t - c - h^0 coupling λ_{tc} is precisely the largest [8]. It is furthermore possible that only u -type quarks have FCNC couplings, while neutral Higgs couplings to d -type quarks and charged leptons are diagonal as in SM and standard 2HDM. In this variant [8], stringent limits from $\mu \rightarrow e\gamma$ [19] and $K^0 - \bar{K}^0$ mixing, *etc.*, are evaded, while limits from $D^0 - \bar{D}^0$ mixing are rather forgiving, so m_{h^0} and/or λ_{tc} are practically unconstrained. We remark that, within the context of *general* 2HDM, neutral Higgs boson mass limits from LEP [4] are weakened, and $m_{h^0} < M_Z/2$ is still allowed.

We assume $h^0 \rightarrow b\bar{b}$ with approximately SM width and explore

$$m_{h^0} < m_t - 10 \text{ GeV}, \quad \lambda_{ct} \geq \sqrt{2m_c m_t}/v, \quad (7)$$

The $t \rightarrow cb\bar{b}$ [8,9] final state is purely hadronic, and is very suppressed in SM. For both scalar and pseudoscalar h^0 , for the range of eq. (7), $\Gamma' = \Gamma(t \rightarrow ch^0) \cong (\lambda_{ct}^2/32\pi) m_t (1 - m_{h^0}^2/m_t^2)^2 \geq 0.049 m_c m_t^2/16\pi v^2$. Together with $\Gamma_{tot}^{SM} = \Gamma(t \rightarrow bW^*)$, B' and $B_{s.l.}$ can be readily estimated from eq. (5). Note that $B' = 1 - R$ is the $t \rightarrow ch^0$ branching ratio. We plot m_t *vs.* R in Fig. 2 for various parameters satisfying eq. (7). Compared with Fig. 1, it is clear that a large parameter range is allowed, especially for light m_{h^0} and large λ_{ct} .

The second mode is $t \rightarrow bH^+$ followed by $H^+ \rightarrow c\bar{s}$ [10]. We remark that recent data [13] on $b \rightarrow s\gamma$ and $B \rightarrow K^*\gamma$ are in good agreement with SM expectations, which implies [12] that $m_{H^+} > m_t$ in SUSY type of 2HDM. This rules out the possibility of $B(t \rightarrow b\tau^+\nu) \rightarrow 1$. However, in *non-SUSY type of 2HDM*, where t - b - H^+ coupling is of the form $\frac{\sqrt{2}}{v} V_{tb} \cot \beta \bar{t} (m_t L - m_b R) b + h.c.$, one obtains the rough limit $\tan \beta \lesssim 0.5$ for light m_{H^+} [12]. (Note that one could also have charged Higgs bosons from “nonstandard” 2HDM’s that possess FCNC Higgs couplings.) We

plot m_t vs. R in Fig. 3 for various parameters satisfying $41 \text{ GeV} < m_{H^+} < m_t - 10 \text{ GeV}$ and $\tan \beta > 0.5$. Note that since H^+ couplings share a common $\cot \beta$, the relative rate for $H^+ \rightarrow c\bar{s}$ vs. $\tau^+\nu$ is roughly $3m_c^2 : m_\tau^2$.

As noted earlier, $1 - R$ is the yet unobserved $t \rightarrow ch^0$ or $t \rightarrow bH^+$ branching ratio. As $R \rightarrow 0$, so $B' \rightarrow 1$, one should look for *direct* observables from these decay modes. For $t \rightarrow cb\bar{b}$, both b jets should be harder than the single b -jet from $t \rightarrow bW^*$ decay. This is because the virtual W tends to be as close to mass shell as possible. Hence, one possible way to identify $t \rightarrow ch^0 \rightarrow cb\bar{b}$ in case it predominates is to tag for (relatively) high p_T multiple b -jets [20]. For the $t \rightarrow bH^+$ mode, clearly $t \rightarrow bc\bar{s}$ would be difficult to disentangle from multijet background, unless b tagging *plus* charm tagging can work together rather well. The better hope is to utilize the $t \rightarrow b\tau^+\nu$ mode, which accounts for $1/3 - 1/4$ of $t \rightarrow bH^+$ transitions in non-SUSY type of 2HDM's. Thus, CDF and D0 should continue the $t \rightarrow bH^+ \rightarrow b\tau^+\nu$ search of UA1/UA2 [11] for the mass region of eq. (4), but allowing $B(t \rightarrow b\tau\nu) \lesssim 1/3$.

Some discussion is in order. First, m_t in the range of eq. (4) is more "normal" since $m_t/m_b \sim m_c/m_s$. However, the global fit of eq. (1) now implies $[4] m_t^2 + \sum_i (c_i/3)\Delta m_i^2 < (194 \text{ GeV})^2$, where $c_i = 1(3)$ for color singlets(triplets), and $\Delta m_i^2 \geq (m_1 - m_2)^2$ is the splitting in *new* weak doublets. If Δm_i^2 comes solely from the extra Higgs doublet, $|m_{H^+} - m_{h^0}|$ should be of order 300 GeV. It may be more plausible to have a fourth generation with $|m_{t'} - m_{b'}| \lesssim 150 \text{ GeV}$. A heavy, fourth generation is favored from the point of view of dynamical symmetry breaking [21]. The new neutral heavy lepton, however, has to be heavier than $M_Z/2$ to satisfy neutrino counting in Z decay [4], which is itself an interesting situation. Although the b' quark may also be obscured by scalar induced decay (or loop-induced FCNC decay [22]), t' decay should be dominated by $t' \rightarrow (b, b') + W$, where W is on-shell ($B(t' \rightarrow th^0)$ should be less than $1/2$). Thus, *even if a "top"-like signal (isolated $\ell^\pm + \text{missing } E_T$) is discovered at the Tevatron, it may well be due to t' (or b') rather than t , and much work would be needed to clarify the actual flavor involved!*

Second, working along the lines sketched in Fig. 1, with diligence and luck a "light top" may surface at the Tevatron. If not, it is reassuring that the mass range of eq. (4) can be fully covered by LEP-II as it turns on in 1997. It would be amusing that not only we would see the crossing of $e^+e^- \rightarrow t\bar{t}$ (and perhaps $b'\bar{b}'$) new flavor threshold, we would actually be able to study *toponium* physics at LEP-II *afterall*. The toponium width would be dominated by single top (scalar induced) decay, but the spectrum would be retained, with rich phenomenology [23]. Third, with extra Higgs doublets and (most likely) new fermion generations, B^0 - \bar{B}^0 mixing can easily be accommodated. Furthermore, B_s - \bar{B}_s mixing is no longer necessarily close to maximal. All considerations regarding CP violation in B sector are enriched, *e.g.* the

unitarity triangle no longer closes.

In summary, new physics due to light scalar particles that preferentially couple to the top, but decay into rather elusive final states, could suppress $B(t \rightarrow \ell\nu + j)$ and thus allow for $m_t < M_W + m_b$, evading the Tevatron bound. The experiments should therefore explore the $m_t - B_{s,l}$ plane. In addition, the process $t \rightarrow ch^0 \rightarrow cb\bar{b}$ may be searched for by tagging multiple high p_T b -jets, while $t \rightarrow bH^+ \rightarrow bc\bar{s}$, $\tau^+\nu$ can be studied by searching for $b\tau\nu$, but assuming $B(t \rightarrow b\tau\nu) \lesssim 1/3$. The standard electroweak fit result of $m_t \sim 150$ GeV would imply large splittings in other weak doublets, such as a 4th generation. Hence, it may be the t' quark that gets discovered at Tevatron in 1994. If $m_t > M_W$ cannot be demonstrated at the Tevatron beyond doubt, the top may show up at LEP-II. If the scenario is realized, there would be *very rich* phenomena unfolding in the near future. After being elusive for 15 years, the top quark may surprise us once again.

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FIG. 1. Schematic limit of m_t *vs.* $R \equiv B_{s,l}/B_{s,l}^{SM}$ for dilepton (+) and single lepton (*) signals, scaled from 1989 CDF data. The region below the curve is ruled out.

FIG. 2. Effect of $t \rightarrow ch^0$ mode. The dotted, dashed and solid curves are for $m_{h^0} = m_t - 10, 20, 30$ GeV, respectively, while each set (from below) corresponds to $\lambda_{ctv}/\sqrt{2m_c m_t} = 1, 2, 4$.

FIG. 3. Effect of $t \rightarrow bH^+$ mode. The dotted, dashed and solid curves are for $41 \text{ GeV} < m_{H^+} = m_t - 10, 20, 30$ GeV, respectively, while each set (from below) corresponds to $\cot \beta = 0.5, 1, 2$.

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